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SWellEx-3 (Shallow Water evaluation cell Experiment 3) was conducted in July 1994 west of Point Loma in 200-m water. During the experiment, a MPL 64-element, 120-m aperture vertical array was deployed on the ocean bottom from the R/P FLIP. Located 2 m above the shallowest array element was a self-recording package equipped with depth, tilt, and direction-of-tilt sensors, thereby permitting array element localization (AEL) to be performed nonacoustically. In addition, AEL was performed acoustically using two different approaches. The first approach made use of transponder pings (in the vicinity of 12 kHz) received by high-frequency hydrophones spaced every 7.5 m along the vertical array. The second approach was based on a self-cohering technique where matched-field processing was performed on a low-frequency, multitone (50–200 Hz) sound source being towed at various ranges and azimuths from the array. The focus of this paper is on a comparison of the time-evolving array shape estimates generated by these three different methods. As shown, all three provide a consistent picture of array motion throughout the 6 hour period analyzed.

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Comparison of Acoustic and Non-Acoustic Methods of Vertical Line Array Element Localization

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Abstract

SWellEx-3 (Shallow Water evaluation cell Experiment #3) was conducted in July 1994 west of Point Loma in 200 m water. During the experiment, a MPL 64-element, 120-m aperture, vertical array was deployed on the ocean bottom from the R/P FLIP. Located 2-m above the shallowest array element was a self-recording package equipped with depth, tilt, and direction-of-tilt sensors, thereby permitting array element localization (AEL) to be performed non-acoustically. In addition, AEL was performed acoustically using two different approaches. The first approach made use of transponder pings (in the vicinity of 12 kHz) received by high frequency hydrophones spaced every 7.5 m along the vertical array. The second approach was based on a self-cohering technique where matched-field processing was performed on a low frequency, multi-tone (50-200 Hz) sound source being towed at various ranges and azimuths from the array. The focus of this paper is on a comparison of the time-evolving array shape estimates generated by these three different methods. As shown, all three provide a consistent picture of array motion throughout the 6 hour period analyzed.

Introduction

Coherent processing of the data from an array of sensors (beamforming) requires an accurate estimate of the sensor positions. As a rule of thumb, the sensors positions must be known to better than (λ /10) at the frequency of interest in order to achieve less than 1 dB loss in (non-adaptive) array processing gain due to errors in array element positions [1]. The need for precise AEL is more important when adaptive array processing is used.

Typically, array element localization (AEL) for a fixed (i.e. bottomed) array is performed by transmitting broadband pulses at several well-navigated locations around the array. The pulses either can be generated by a towed source or by explosive/implosive shots (e.g. lightbulbs) [2]. Similarly, a towed CW source also can be used to localize the elements of an array. The arrival structure of these purposefully-generated signals contains the information needed to determine array shape.

In the case of a vertical array, the array shape is dynamic and thus AEL must be performed continuously. The focus of this paper is on a comparison of array shape results from three different approaches to AEL applied to experimental data from a shallow water vertical array.

Experiment: SWellEx-3

SWellEx-3 (Shallow Water evaluation cell Experiment #3) was conducted in July 1994 west of Point Loma in 200 m water. During the experiment, a MPL 64-element, 120-m aperture, vertical array was deployed on the ocean bottom from the R/P FLIP (see Figure 1).

Located 2 m above the shallowest array element was a self-recording package equipped with depth, tilt, and direction-of-tilt (heading) sensors, thereby permitting array element localization (AEL) to be performed non-acoustically. In addition, AEL was performed acoustically using two different approaches.

The first acoustic approach made use of the data collected by high frequency hydrophones spaced every 7.5 m along the vertical array (16 AEL sensors total). Four common-interrogate/unique-reply transponders, with reply pings centered at 9.5, 10.0, 10.5, and 11.5 kHz, were deployed approximately every 90° about the vertical array at a range of 500 m. These transponders were interrogated every 15 sec by a hull-mounted transducer at the base of R/P FLIP (about 90 m below the ocean surface). A second hull-mounted transducer recorded the transponder replies as well as the interrogations which enabled a determination of the FLIP-transponder travel time. Since FLIP moves in her mooring (as much as 50 m during SWellEx-3) in response to current and wind forces, these FLIP-transponder travel times evolve over time. The transponder replies also were received by the AEL sensors yielding the FLIP-transponder-array travel times. By subtracting out the FLIP-transponder travel times, the travel times from the (fixed with known location) transponders to the AEL sensors were derived. These travel times (converted to slant-ranges) then were used in a nonlinear least-squares algorithm to determine the AEL sensor positions (e.g. see [3] for an example of transponder-based AEL in deep water). Since the vertical array also responds to (depth-dependent) current forces, its shape evolves over time and must be tracked continuously.

The second acoustic approach was based on a self-cohering technique where matched-field processing was performed on a low frequency, multi-tone (50-200 Hz) sound source being towed at various ranges and azimuths from the array. Figure 2 shows the tow ship track history over the period of interest (the R/P FLIP and the vertical array are located at Point O). Using estimates of the water column sound speed structure, bathymetry, and geoacoustic properties of the bottom, a propagation model was used to calculate the predicted acoustic field at the array (replica vector) for various hypothesized ranges, depths, and azimuths of the sound source, and for a range of tilts of the array (treated as a rigid line). The data observed on the array then was cross-correlated with these replica vectors (conventional matched-field processing [5]) with the peak in this multidimensional search space providing estimates of source range, depth, and azimuth as well as array tilt (in the direction of the sound source). Additional discussion concerning the use of matched-field processing to perform array surveying can be found in [5-6]. More detailed discussion of matched-field processing results from SWellEx-3 can be found in [7-10].

Array Element Localization (AEL)

The period examined from SWellEx-3 was 30 July 1994 (JD 211) 1240-1840 Z or 6 hours. The results from each of the three approaches of array shape estimation will be presented and discussed in the following section.

Nonacoustic (Inclinometer)

As noted previously, the inclinometer (tilt-heading sensor) was attached to the array cable at a location 2 m above the uppermost array hydrophone (a depth of approximately 72 m). Plots of the inclination of the array from vertical and direction of tilt at this point over the 6 hour period are shown in Figure 3. The direction of tilt (heading) essentially is 0° (northward) throughout this period. The inclination from vertical (tilt) is relatively constant at 2° for the first three hours then steadily increases to approximately 5.5° over the next three hours.

High Frequency (Transponder)

Transponder localization of the array elements was performed as discussed above. Plots of time-evolving array shape over the 6 hour period are shown in Figure 4. Each array shape displayed represents a half-hour average (AEL estimates are generated every 15 seconds). The 12 array shapes are numbered in sequence {0, 1, 2, ..., 9, A, B}. There are 16 positions along the array which are navigated and these are indicated by the corresponding shape sequence number. The X coordinate is positive towards the east and the Y coordinate is positive towards the north. The array is almost vertical in the east-west vertical plane but has significant inclination towards the north in the north-south vertical plane (along with a noticeable concave upward character). The temporal dynamics of the array shape appear relatively benign in the east-west vertical plane. In the north-south vertical plane, the array shape changes little for the first three hours but changes substantially over the last three hours (the upper AEL sensor moves approximately 10 m towards the north over this period).

Low Frequency (Self-Cohering)

Array tilt in the direction of the sound source was estimated using the self-cohering, matched-field processing technique described earlier. Plots of the time-evolving array tilt over the 5 hour period 1240-1740 Z are shown in Figure 5. From the experiment log and the tow ship range and bearing plots shown in Figure 6, the tow ship track was as follows (see Figure 2): (a) vicinity of Point 1 (1244-1320 Z), (b) northerly radial track Points 1-to-2: (1320-1347 Z), (c) arc track Points 2-to-3 (1347-1447 Z), (d) westerly radial track Points 3-to-4 (1447-1514 Z), (e) arc track Points 4-to-1 (1514-1547 Z), (f) southerly radial track Points 1-to-5 (1547-1612 Z), (g) north-easterly radial track Points 6-to-7 (1612-1703 Z), (h) south-westerly radial track Points 7-to-6 (1703-1800 Z), and (i) northerly radial track Points 5-to-1 (1800-1820 Z). The self-cohering-derived array tilt is 6-7° degrees while the tow ship is going north (1240-1400 Z), 0° while the tow ship is going west (1440-1520 Z), approximately 5° while the tow ship is going south (1540-1610 Z), and gradually increases from approximately 5 to 7° while the tow ship is going northeast then southwest (1610-1740 Z).

Discussion

As is evident from Figures 3-5, the time-evolving array shape estimates generated by all three AEL approaches provide a consistent picture of array motion throughout the 6 hour period.

The inclinometer data in Figure 3 shows a steady northward tilt of the top of array for the first three hours then an increasing northward tilt for the last three hours. Treated as a rigid line array, the 2° tilt observed early in the period corresponds to 4.2 m horizontal displacement and the 6° tilt observed at the end of the period corresponds to a 12.5 m horizontal displacement. These horizontal displacements are both significantly less than reported by the transponder AEL results shown in Figure 4. However, there is a noticeable catenary to the array. In future experiments, the addition of inclinometers at the center and bottom of the array would enable resolving array curvature.

The self-cohering, matched-field processing results shown in Figure 5 also indicate that the array has a northward tilt. As a consequence of the analysis technique, the reported tilt always is in the direction of the low frequency acoustic source. The source ship begins on a northward course and the array (treated as a rigid line) appears tilted at 6-7° in that direction. As noted above, a 6° tilt corresponds to a 12.5 m horizontal displacement across the 120 m array aperture. This

displacement is consistent with the transponder AEL results shown in Figure 4b. After the arc track, the source ship moves along a westerly course and the array appears tilted approximately 0° in that direction (see Figure 5). These results also are consistent with the transponder AEL results shown in Figure 4a. Finally, during the last 1-1/2 hours represented in Figure 5 (1610-1740 Z), the source ship traverses a radial track northeast and returns along the same track southwest. Over this period, the array appears to increase in tilt (in that direction) from 5 to 7°. A 5° tilt corresponds to a 10.5 m horizontal displacement of the array and a 7° tilt corresponds to a 14.6 m horizontal displacement of the array. As expected, these displacements are less than the transponder AEL results shown in Figure 4b since the source ship track in not northward but along a bearing of approximately 35°. Thus, only a projection of the full array tilt is observed.

The transponder array element localization results shown in Figure 4 provide the most detailed picture of the time-evolving array shape. The array appears to undergo relatively little motion during the first three hours. Over the last three hours, however, significant northward movement of the array is observed. This motion is consistent with wind and current forces acting on the recording platform (R/P FLIP). Differential GPS measurements of FLIP motion during this period (not shown) indicate relatively little motion of FLIP during the first three hours of this period but a movement of approximately 7.5 m northward over the last three hours. Although the array was decoupled from FLIP as best as possible (significant buoyancy on the top of the array and a relatively slack tether to FLIP for the array umbilical cable), it appears that FLIP actually was pulling slightly on the array.

Summary

The focus of this paper has been on a comparison of vertical array shape results from three different approaches to array element localization. The three methods were: (1) nonacoustic where an inclinometer (tilt-heading sensor) was placed just above the top element of the array, (2) high frequency (in the vicinity of 12 kHz) acoustic transponder navigation, and (3) low frequency acoustic self-cohering using matched-field processing. As evident from Figures 3-5, the time-evolving array shape estimates generated by all three AEL approaches provide a consistent picture of array motion throughout the 6 hour period. Although the array shape evolves gradually, significant motion was observed over as little as 1/2 hour. A noticeable catenary is present in the array shape. Thus, although a simple rigid line array model is adequate to describe the gross motion dynamics of the array, tracking several points along the aperture is desirable for a detailed shape characterization.

Acknowledgments

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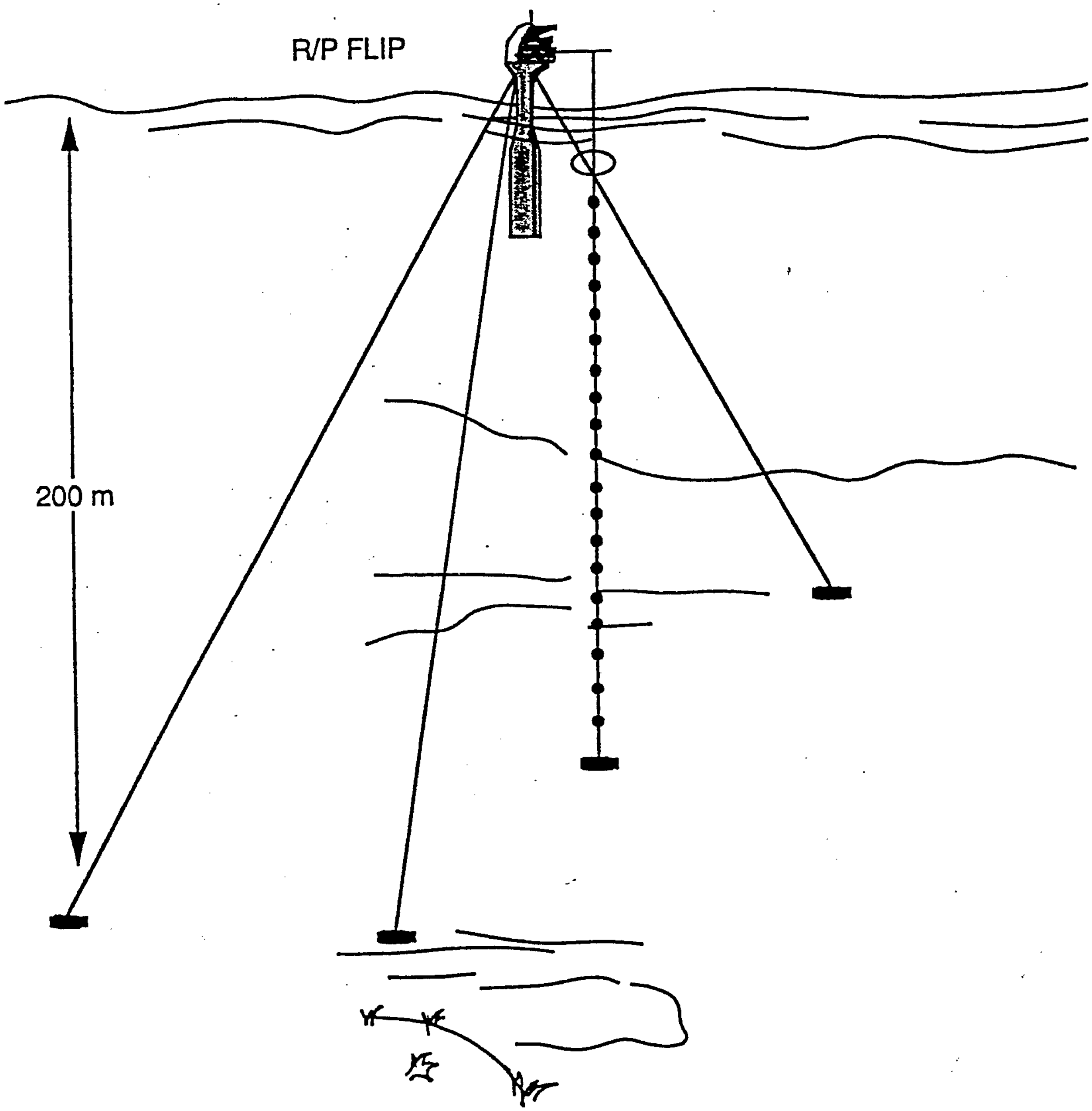

Figure 1. Vertical array deployed from the R/P FLIP during SWellEX-3.

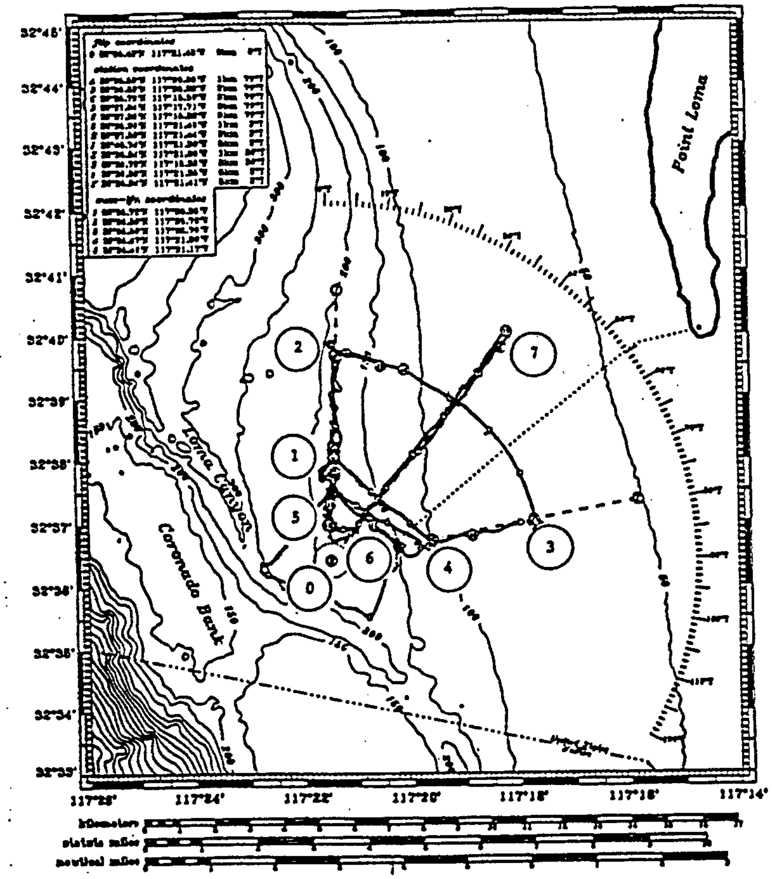

Figure 2. DPGS track of source ship: 30 July 1994 (JD211) 1100-1800z.

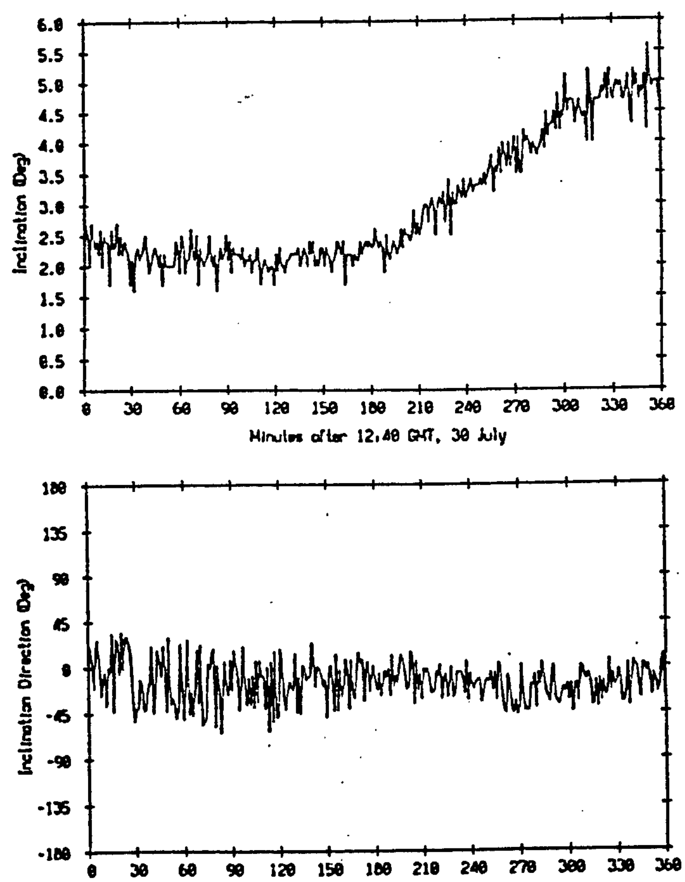

Figure 3. Inclination of array from vertical and direction of tilt.

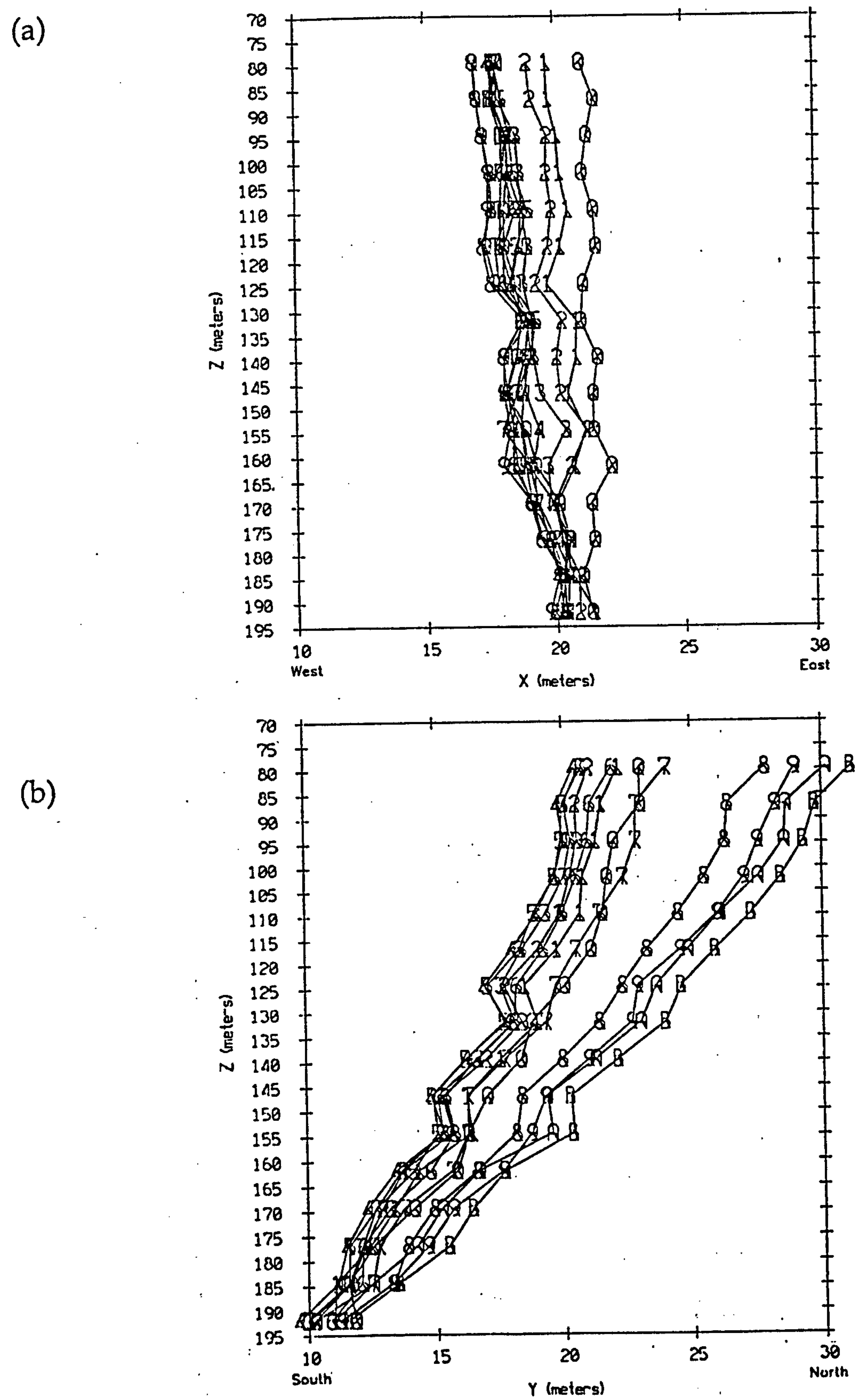

Figure 4. Transponder localization of array elements: (a) x(east) vs. z(depth); (b) y(north) vs. z(depth).

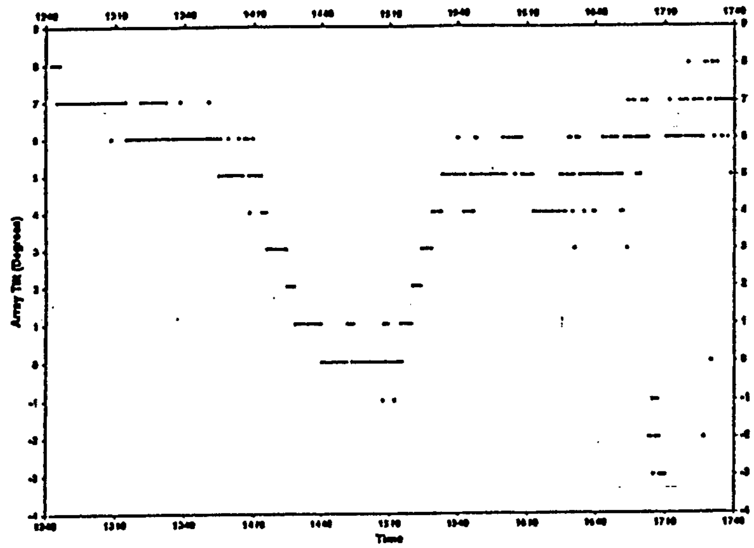

Figure 5. Matched field processing estimation of array tilt.

(a)

(b)

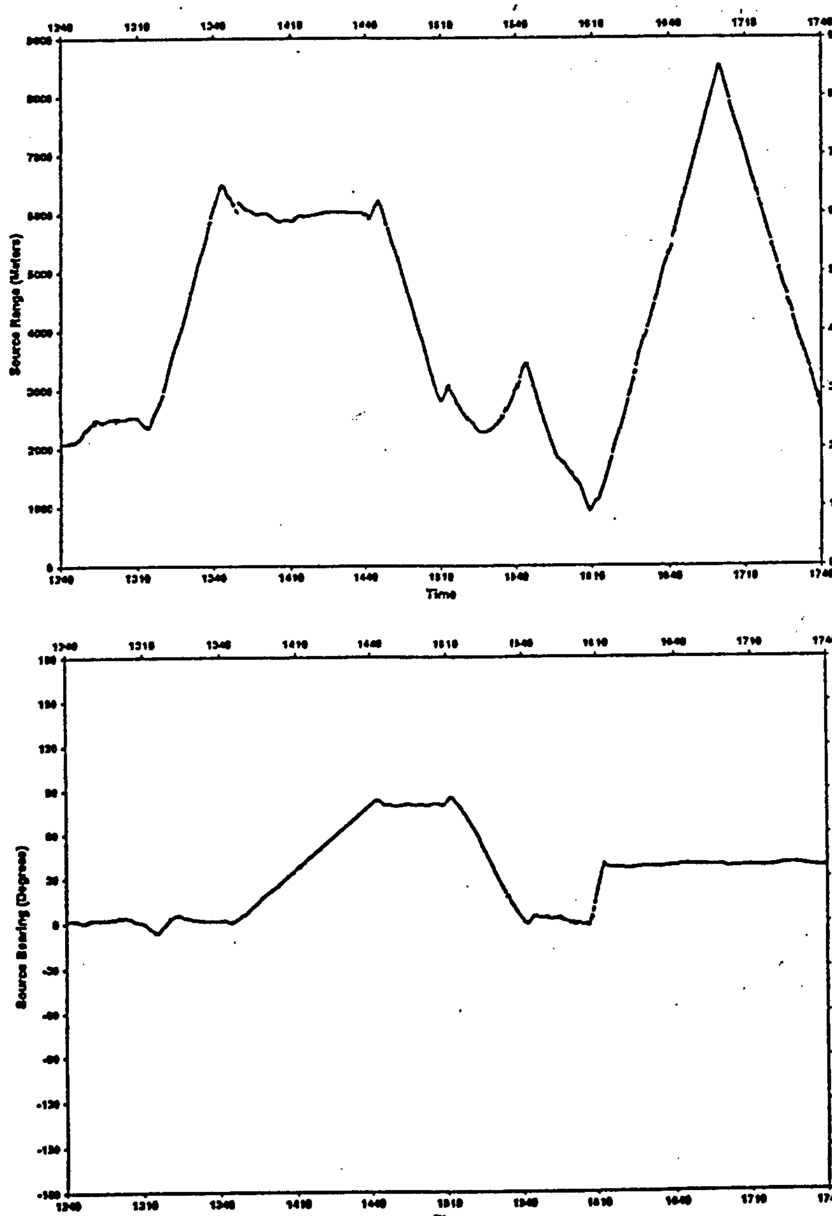

Figure 6. DPGS source ship track: (a) range vs. time; (b) bearing vs. time.

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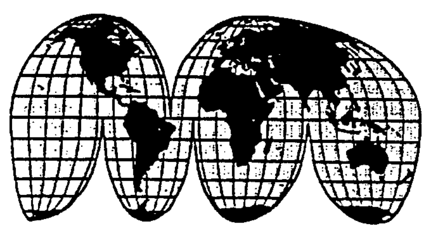

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